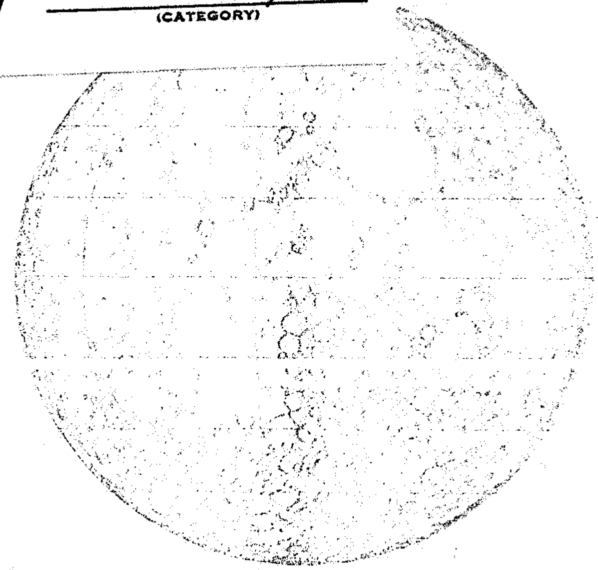
ASTROGEOLOGIC STUDIES

ANNUAL PROGRESS REPORT

July 1, 1966 to October 1, 1967



DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

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December 1967

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INTRODUCTION

This Annual Report is the eighth of a series describing the results of research by the U.S. Geological Survey on behalf of the National Aeronautics and Space Administration under contract R-66. The report was prepared by the Branch of Astrogeologic Studies, previously the Astrogeologic Studies Section of the Branch of Astrogeology. The other former section is now the Branch of Surface Planetary Exploration, and work done by its personnel for the Branch of Astrogeologic Studies is also described here. This report covers July 1, 1966 to October 1, 1967; 15 rather than 12 months are covered so that future report periods will correspond to contract years. This one-volume summary replaces the multi-volume annual reports of previous years. Supplemental maps are no longer included but are distributed as they are completed.

Long-range objectives of the astrogeologic studies program are to determine and map the stratigraphy and structure of the crust of the Moon and other planets, to determine the sequence of events that led to the present condition of the surfaces of the planets, and to describe how these events took place. Work currently leading toward these objectives includes: (1) a program of lunar geologic mapping from both telescopic and spacecraft photographs supported by photometric studies; (2) field studies of natural structures of impact and volcanic origin and of craters produced by missile impact and explosive devices; (3) laboratory studies of the behavior of rocks and minerals subjected to shock; (4) study of the chemical, petrographic, and physical properties of tektites, meteorites, and cosmic dust and development of specialized analytical techniques.

This volume comprises four sections, each corresponding to an entire volume of previous years. Part A, Lunar and Planetary Investigations, discusses the program of lunar geologic mapping, including (1) regional mapping at a scale of 1:1,000,000; (2) synoptic compilation of the mapping results at the 1:5,000,000 scale; (3) Apollo site mapping at the 1:100,000, 1:25,000, and 1:5,000 scales; (4) Ranger mapping at a variety of scales. Part B, Crater Investigations, reports progress in field and laboratory studies of craters and related phenomena. Field investigations are being made of naturally formed craters and roots of craters of impact and volcanic origin: (1) Flynn Creek, Tennessee; (2) Sierra Madera, Texas; (3) Gosses Bluff, Australia; (4) Mule Ear diatreme, Utah; (5) Moses Rock diatreme, Utah; (6) Lunar Crater, Nevada; (7) San Francisco volcanic field, Arizona; and (8) Ubehebe Crater, California. Impact-metamorphosed rocks and minerals from several large impact structures are being intensively studied in the laboratory. Man-made craters that are being studied range from those produced by missile impact at White Sands Missile Range to those formed in sand by small low-velocity projectiles. Part C, Cosmic Chemistry and Petrology, includes reports on techniques of study, analysis, and interpretation of data on materials of known or suspected extraterrestrial origin. Part D, Space Flight Investigations, covers studies from Surveyor photographs and includes a brief summary of work done in support of space flight operations, mainly of Surveyor and Orbiter but including preliminary planning for Mars vehicles that necessarily accompanies data gathering for planetary studies.

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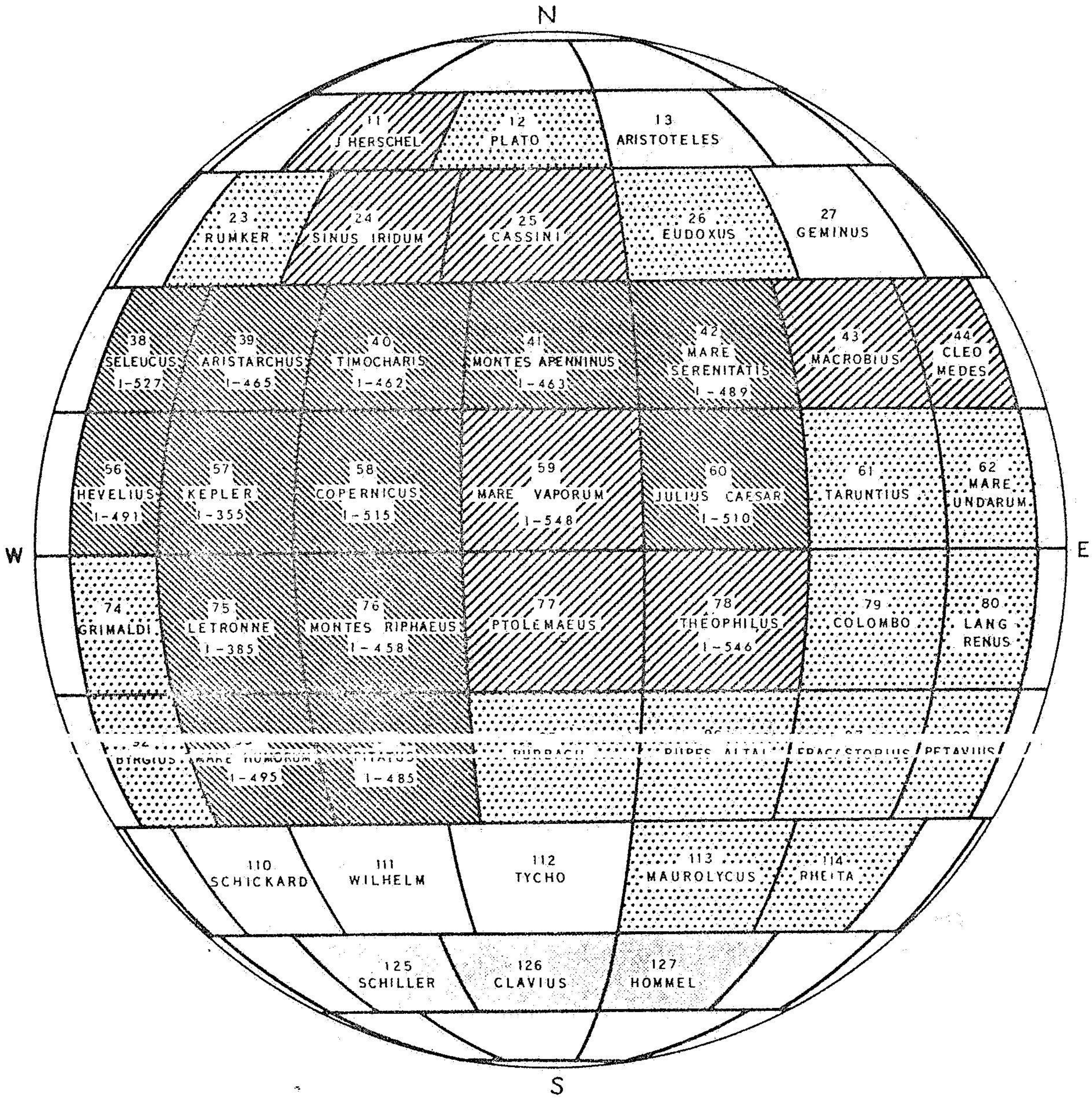
Part A. LUNAR AND PLANETARY INVESTIGATIONS

During contract year 1967, the lunar and planetary program concentrated on Lunar Orbiter and Surveyor space flights. Photographs and other data from these highly successful spacecraft were screened, mainly for their application to the Apollo program, and an intensive program of mapping Apollo sites was begun. In addition, mission operations (reported in Part D) occupied the time of 10 lunar geologists during space flights. As a result, few new 1:1,000,000 scale maps were completed, although substantial progress was made on those of the 44 quadrangles at this scale that are contracted for but as yet unpublished. Work also advanced on a 1:5,000,000 earthside compilation.

I. Mapping at a scale of 1:1,000,000

Progress report

During the period July 1966 to October 1967, progress was made toward the eventual publication of 1:1,000,000 maps of the entire lunar earthside hemisphere (tables 1-3). Seven maps whose content was summarized in the previous annual report (Seleucus, Pitatus, Mare Humorum, Mare Serenitatis, Hevelius, Julius Caesar, Copernicus) were published. All of these are in the central and western parts of the equatorial belt of 28 quadrangles where the lunar geologic mapping program began; 12 maps in this belt of quadrangles are now published (fig. 1, table 1). One map that also was summarized last year (Mare Vaporum) is completed and will soon be published (table 1). Two additional maps in this belt were readied for publication and are summarized in this report; one (Theophilus) was submitted for publication but has been considerably delayed because of base-registration problems; another (Ptolemaeus) is in the final editorial stages; both will be published in fiscal year 1968. Three preliminary maps in the northwest quadrant of the Moon completed last year (Cassini,



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Unreviewed author-drafted version

Figure 1.--Index map of Moon showing 1:1,000,000 maps available for distribution as of December 1967.

Table 1.--Maps at 1:1,000,000 scale published or in press at end of contract year 1967 (publication date of maps not yet printed indicated by parentheses)

Map	Author	Number	Publication date
Kepler	Hackman	I-355	1962
Letronne	Marshall	I-385	1963
Riphaeus Mts.	Eggleton	I-458	1965
Timocharis	Carr	I-462	1965
Aristarchus	Moore	I-465	1965
Montes Apenninus	Hackmann	I-463	1966
Pitatus	Trask, Titley	I-485	1966
Mare Serenitatis	Carr	I-489	1966
Hevelius	McCauley	I-491	1967
Mare Humorum	Titley	I-495	1967
Julius Caesar	Morris, Wilhelms	I-510	1967
Copernicus	Schmitt, Trask, Shoemaker	I-515	1967
Seleucus	Moore	I-527	1967
Mare Vaporum	Wilhelms	I-548	(early 1968)
Theophilus	Milton	I-546	(mid-1968)
Ptolemaeus	Howard, Masursky	none assigned*	(mid-1968)

*The Ptolemaeus quadrangle was not yet in press at the end of fiscal year 1967; it will be submitted in December 1967.

Sinus Iridum, J. Herschel) have been revised, and will soon be submitted for publication (table 2); they are discussed here in the light of Orbiter data. Four preliminary maps of quadrangles in the eastern part of the Moon completed 2 years ago are being revised for publication and should also be published in fiscal year 1968 (table 2). Two of these (Macrobius, Cleomedes) as wellas all the unpublished maps so far discussed are available in substantially revised form (fig. 1); author's working copies of two others (Taruntius, Colombo) can be consulted. Work towards a published version also progressed on five other previously submitted preliminary maps (Rupes Altai, Plato, Langrenus, Purbach, Grimaldi) (table 2).

Among the uncolored ozalid preliminary maps not previously completed, one of a quadrangle in the northeast quadrant of the Moon (Eudoxus) was completed in fiscal year 1967 and is being revised for publication (table 2). Three maps of quadrangles in the southern highlands (Hommel, Clavius, Schiller) were brought near to completion (table 3). Two in the northeast (Aristoteles, Geminus) and three in the southern highlands (Tycho, Wilhelm, Schickard) are less advanced but will be finished in preliminary form before October 1968. These five are the last of the group of 44 quadrangles originally assigned, and with their completion approximately one-third of the Moon (total, 144 quadrangles) will be mapped at least in preliminary form.

Quadrangle and regional summaries

Highlands (terra) occupy most of the Theophilus quadrangle. Stratigraphic correlation of the highlands units with the standard lunar stratigraphic section in the Imbrium region proved difficult, and units were discriminated primarily on the basis of the local physiographic characteristics. The three principal units as mapped by D. J. Milton are characterized by (1) level flat or gently undulating low-lying plains (Cayley Formation), (2) rolling plateaus of smooth surface texture (material of Kant

Table 2.--Maps at 1:1,000,000 scale previously completed in preliminary form and now being revised for publication. Percentage completion and estimated completion refer to author's work; review, drafting, and printing require 8 to 10 additional months

Map	Author	Percent revision is complete Oct. 1	Dec.	Estimated completion
Cassini	Page	35	100	12/67
Sinus Iridum	Schaber	50	90	1/68
J. Herschel	Ulrich	20	90	1/68
Macrobius	Pohn	50	90	2/68
Cleomedes	Binder	90	90	2/68
Colombo	Elston	90	90	2/68
Taruntius	Wilhelms	60	70	2/68
Eudoxus	Page	0	50	3/68
Rupes Altai	Rowan	15	40	3/68
Plato	M'Gonigle, Schleicher	15	50	3/68
Grimaldi	McCauley	10	30	4/68
Purbach	Holt	25	25	5/68
Langrenus	Cannon,* Wilhelms, Ryan	20	30	7/68
Petavius	Holm,* Wilhelms	0	5	8/68
Fracastorius	Elston	0	0	9/68
Rümker	Eggleton, Smith	0	0	FY 69
Rheita	Stuart-Alexander	0	0	FY 69
Maurolycus	Cozad, Titley	0	5	FY 69
Byrgius	Trask	0	0	FY 69
Mare Undarum	Masursky, Colton*	0	0	FY 69

*Recent reassignment.

Table 3.--Maps at 1:1,000,000 scale being prepared in preliminary form. Figures refer to completion of author's work; review, drafting, and ozaliding require 4 additional months; publication should follow about a year after that (16 to 18 months from dates given)

Map	Author	Percent revision is complete Oct. 1	Dec.	Estimated completion
Clavius	Cummings	100	100	8/67
Hommel	Mutch, Saunders	90	100	10/67
Schiller	Offield	40	100	12/67
Aristoteles	Roddy	20	30	1/68
Schickard	Karlstrom	5	30	3/68
Geminus	Grolier	5	10	3/68
Tycho	Pohn	35	35	4/68
Wilhelm	Saunders,* Wilhelms*	5	15	5/68

*Recent reassignment.

Plateau), and (3) rugged irregular hills (terra units). The near-surface materials in all three units may be mostly of volcanic origin, although much of the characteristic relief of the units is that of underlying features that may be of impact or tectonic origin. Relative age of the three surface units cannot be established. The units all apparently post-date the formation of the Imbrium basin, but range up into the Copernican System.

History of terra areas in the Ptolemaeus quadrangle, mapped by Keith A. Howard and Harold Masursky, is complex. Pre-Imbrian regional deposits are suggested by plateaus, such as the region northwest of Ptolemaeus, that lie between remnants of some of the many ancient craters. Pronounced faults radial to Mare Imbrium (Imbrian sculpture) were evidently produced by the

Imbrium impact. Evidence of reactivation of the sculpture is presented by the rilles and scarps in Ptolemaeus, Alphonsus, and Hind that follow the sculpture direction but are younger than the Imbrian material which fills these craters. This fill, the smooth, plains-forming Cayley Formation, occupies most other terra depressions in the quadrangle as well, and here, as in other regions of the southern highlands, appears to grade laterally into a thin mantle of material that smooths large areas of intervening hills. The Cayley and this apparent thin equivalent are interpreted either as the result of mass wasting or as ash flows. Various volcanic landforms occur in the quadrangle, including pitted uplands near Müller, dark-halo craters in Alphonsus, the bright-halo crater Davy G, and craters as much as 17 km wide in the Vogel chain. Age relations indicate volcanic-crater formation in the terra from Copernican back through at least Imbrian time, and impact cratering throughout the decipherable history of the quadrangle.

All 1:1,000,000 maps made or revised after the flight of Lunar Orbiter IV (that is, those listed in tables 2 and 3) will benefit from the superb photographs obtained by that spacecraft; mapping will be more meaningful and will progress faster. An important example of this is the increased understanding of the origin of terrain surrounding mare basins that was made possible by Lunar Orbiter IV photographs of the Mare Orientale basin. Structures and geologic units of Orientale are fresh and relatively unmodified by erosion, tectonism, and post-basin deposits. By comparing them with the degraded structures and units of other basins, the elements of the other basins dating from the time of basin formation can now be discriminated from those produced by later events.

Such a comparison has been made between Imbrium and Orientale and has led to clarification of terrain inside the Apennine scarp and north of the Imbrium basin. There are three major components in this terrain: a set of concentric structural rings formed simultaneously with the basin, surface units also most likely contemporaneous with the basin (probably ejecta), and post-basin materials. Matching of the structural rings among basins is a necessary preliminary to matching surface materials. Hartmann and Kuiper (of the Lunar and Planetary Laboratory of the University of Arizona) demonstrated (Ref. 1) that a similar pattern exists among the rings of all frontside basins, but the exact manner of correspondence between Orientale and Imbrium was not known until Orbiter IV photographed the western limb. The photographs show a close match among four principal structural rings of both Orientale and Imbrium: (1) an inner basin (covered in both basins); (2) a ring of peaks (exposed in Orientale; in Imbrium, the inner ring of steep islands--Straight Range, Spitzebergen, etc.--that was previously thought to border the inner basin directly);(3) another ring of peaks (in Orientale the Rook Mountains; in Imbrium, the Alpes and the rugged terrain adjacent to Archimedes): (4) the outer scarp (in Orientale, the Cordillera: in Imbrium, the Apennines and Carpathians and the north edge of Mare Frigoris). This clarification of the relation of the rings of the two basins clarifies the correspondence of the surface deposits. Most significantly, between the third and fourth rings of Orientale (and in depressions outside the fourth ring) is a rough pimply terrain that is like terrain that has long been known near Imbrium but whose relation to the Fra Mauro Formation (a more gently hummocky blanket long interpreted as the ejecta from the Imbrium basin) was not understood. Now that the correspondence of the structural rings is established, it is seen that some of the rugged terrain of Imbrium occurs in the same relative position as that in Orientale, between the third and fourth rings. (The rest, interestingly, may occur in the same position relative to the Serenitatis basin and thus be genetically related to that basin and not to Imbrium.) The outer deposit around Orientale, outside the Cordilleras and called the Cordillera Formation, resembles the Fra Mauro Formation except for its delicately grooved pattern, which presumably has not been preserved in the older Imbrium equivalent. The origin of the inner rugged material is uncertain, although it probably formed along with the basin; the upper surface of the outer material within one basin diameter was apparently emplaced by radial flowage, possibly by a base surge.

Differences between the basins are apparently due to the age of the Imbrium basin. Many of the structural peaks and hills of rough ejecta(?) are smoother in Imbrium than Orientale, and depressions are filled with light plains-forming materials.

These new insights facilitate completion of 1:1,000,000-scale maps of the northern Imbrium region. Three quadrangles (Cassini, Sinus Iridum, and J. Herschel) are in final stages of completion and will be submitted for publication within 2 or 3 months. Two others (Plato and Eudoxus) will also be submitted for publication within FY 1968. Mapping of a quadrangle in the Orientale region (Grimaldi) will also be completed in FY 1968.

Other basins also are now better understood, although they are all older than Imbrium and Orientale, and diagnostic surface textures are accordingly less discernible. However, four raised structures comparable to those surrounding Orientale and Imbrium can be recognized around the Crisium and Nectaris basins (Ref. 1), and progress has been made in matching surface textures with those of the younger basins. For example, rugged terrain around Crisium previously thought to be part of the ejecta of the crater Cleomedes is now thought comparable to the rugged terrain between the third and fourth structural rings of Orientale and Imbrium because the Crisium material also occurs between the third and fourth rings. Little Crisium material comparable to the Fra Mauro and Cordillera Formations outside the fourth ring has been recognized, and the reason is now believed to be susceptibility of the distinctive fine texture of the material to erosion. Many deep radial structures occur here that are very similar to those of Orientale. Another example of a unit now better understood is the Secchi Formation southwest of Taruntius, whose rough surface texture suggested basin impact ejecta but whose distribution argued against this interpretation. It occurs close to the Fecunditatis basin, which seemed excluded as a source because of its great age, and is sporadically distributed relative to the Nectaris basin, otherwise a more likely source. Now it is seen that the Secchi is distributed relative to Nectaris exactly as some of the rough material is distributed relative to Orientale--in a low radial trough outside the main scarp (at Nectaris, a continuation of the Altai Scarp northeast of the basin). Maps soon to be published that will benefit from this improved understanding of Crisium and Nectaris are Cleomedes, Macrobius, Taruntius, and Colombo.

Considerable progress was made in geologic mapping of the southern lunar highlands. First versions of preliminary maps for three quadrangles (Hommel, Clavius, Schiller) were nearly completed in the year and three others (Tycho, Wilhelm, Schickard) were worked on. Stratigraphic units can be correlated between quadrangles, and an integrated geologic history for the region can be developed. There are two broad classes of rock-stratigraphic units: 1) crater materials and 2) plains-forming units. Craters are being mapped according to a classification recently developed especially for use in the highlands, a classification which employs both morphology and crater size as variables (and is similar in concept to the classification used in mapping Apollo sites; see section III). Plains-forming units form level areas both inside and outside craters. Variations in surface texture signify at least three periods of emplacement. There is a general decrease in areal extent of plains units from west to east, possibly an indication of volcanic flooding transgressive from west to east. Plains-forming units--some of them apparently very thick--are superposed on older sculptured and structured terrae. These old surfaces are formed by a complex interaction of cratering, ejecta blanketing, structural disturbance, volcanism, and mass wasting.

Geologic mapping of the type being developed within the southern highlands will probably apply also to similarly rugged highlands which occupy most of the far side of the Moon.

II. Compilations at a scale of 1:5,000,000

A geologic map of the equatorial belt--lats 32° N.-32° S., longs 70° E.-70° W.--at a scale of 1:5,000,000 is being prepared for publication by Don E. Wilhelms and John F. McCauley. This map will supersede a preliminary one compiled in July 1965 by Wilhelms, N. J. Trask, and J. A. Keith (Ref. 2). The new map will have the same areal coverage and about the same density of lines as the old one but will embody improved interpretations of the last 2 years, particularly in terra and mare-basin geology. Like its preliminary predecessor, the map will have as base the ACIC orthographic LEM-1 photographic mosaic. The work of the mappers should be finished in February 1968. Further compilations of this type, on different bases, are planned as more area is mapped and interpretations improve, on the far side as well as the near side.

III. Apollo site mapping

Geologic mapping of prime Apollo sites from Lunar Orbiter photographs began during FY 1967 and is currently being intensively pursued (table 4). The entire medium-resolution Orbiter coverage of eight Apollo sites is being mapped at a scale of 1:100,000 and one ellipse (plus its surroundings) in the high-resolution coverage of each of the eight is being mapped at a scale of 1:25,000 (fig. 2). Each map has already passed through at least two versions and will be improved additionally before publication. Mapping from medium-resolution photographs began with the screening report for each mission (Refs. 3-6; see also Part D); additional sites subsequently rejected for an Apollo mission were also mapped then, as was a ninth site (A-1 or III P-2 or V-8) that will probably become a prime site and will therefore be worked upon additionally. Revisions of these

Table 4.--Apollo site maps in preparation. Second preliminary version is a reviewed, standardized, and drafted revision of an unreviewed earlier author's copy already transmitted to the Manned Spacecraft Center (before 15 November 1967). Semifinal version is refined over the second preliminary and is the version for Apollo mission operations and in most cases for submission for publication; publication should follow completion dates in 8 to 10 months

		Percent completion				
Map	Author	Second preliminary Oct. 1	Second preliminary Dec.	Controlled base reproducibles received	Semifinal as of Dec.	Semifinal estimated completion
			Scale 1:100,000			
II P-2	Carr	100	100	X		3/68
II P-6	Grolier	80	100	X		4/68
II P-8	Rowan	100	100	X		3/68
II P-11	Wilshire	70	100	X		5/68
II P-13	Titley	100	100	X		4/68
III P-9	Pohn	100	100			4/68
III P-11	Cummings	75	100			5/68
III P-12	Offield	100	100			4/68
			Scale 1:25,000			
II P-2	Wilhelms	20	100			3/68
II P-6	Grolier	20	100			6/68
II P-8	Trask	80	100	X		3/68
II P-11	Trask	30	100			3/68
II P-13	Titley	20	100			4/68
III P-9	Saunders	75	100		20	2/68
III P-11	Cannon	5	100			3/68
III P-12	Harbour	20	100			3/68

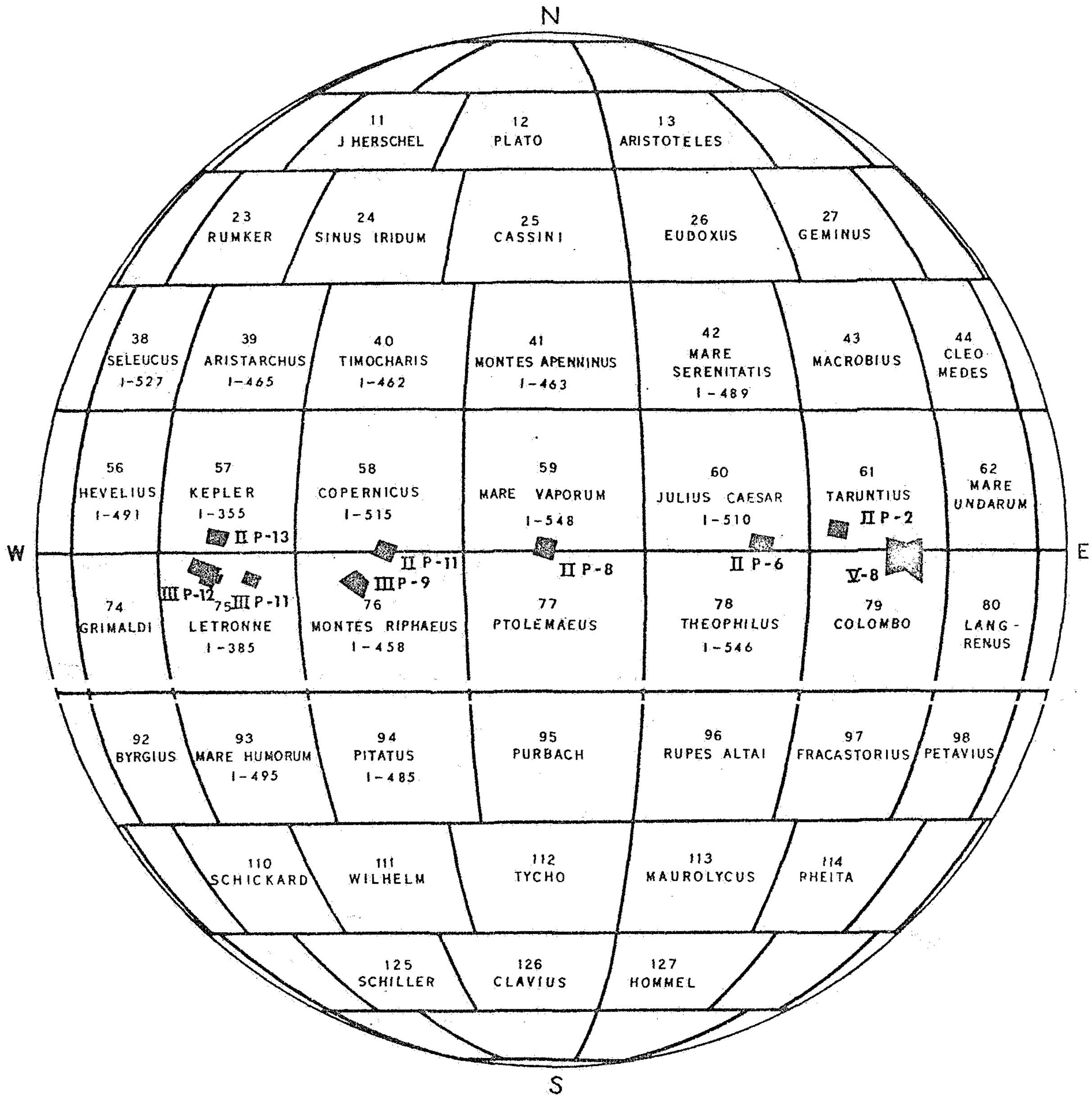

Figure 2.--Apollo sites being mapped geologically from Orbiter photographs.

screening maps on uncontrolled base mosaics at approximately the 1:100,000 scale have been forwarded to the Manned Spacecraft Center, as have first preliminary versions of the 1:25,000 ellipse maps (table 4). Further revisions of the 1:100,000 maps, mostly on controlled mosaics and better standardized with one another, are being transmitted as this report is being written, and revisions of the 1:25,000 maps will follow soon. Additional revisions at both scales will follow as the sites are studied further and thoroughly compared and standardized. They will be published when this process is complete.

Mapping at the 1:5,000 scale of four sites (II P-6, II P-8, II P-13, II P-11) will begin soon.

Because craters are the most abundant, conspicuous and readily mappable topographic features on large-scale Lunar Orbiter photographs, considerable effort has gone into devising a system for the geologic mapping of crater materials. A morphologic range from sharply sculptured, blocky high-rim craters to gentle depressions is common to all map areas. The continuum of crater types suggests that, with time, fresh craters are degraded to gentle depressions. A working assumption for geologic mapping is that all circular craters were originally fresh appearing and have undergone degradation in varying degree. In such a model, small craters would be degraded faster than large ones, so that a relatively small subdued crater might be the same age as a larger sharper-appearing one. The relation between the size, morphology, and age of craters is shown in figure 3. The crater classification scheme is in part arbitrary and in part based on what appear to be reasonable estimates of the relative rates of crater degradation that are consistent with the time scale used earlier in 1:1,000,000 mapping. Where superposition relations are clear, higher-number craters are superposed on lower-number craters in virtually every case encountered in the large-scale mapping so far. Efforts to make the system more objective are underway. The principle uncertainties lie in the

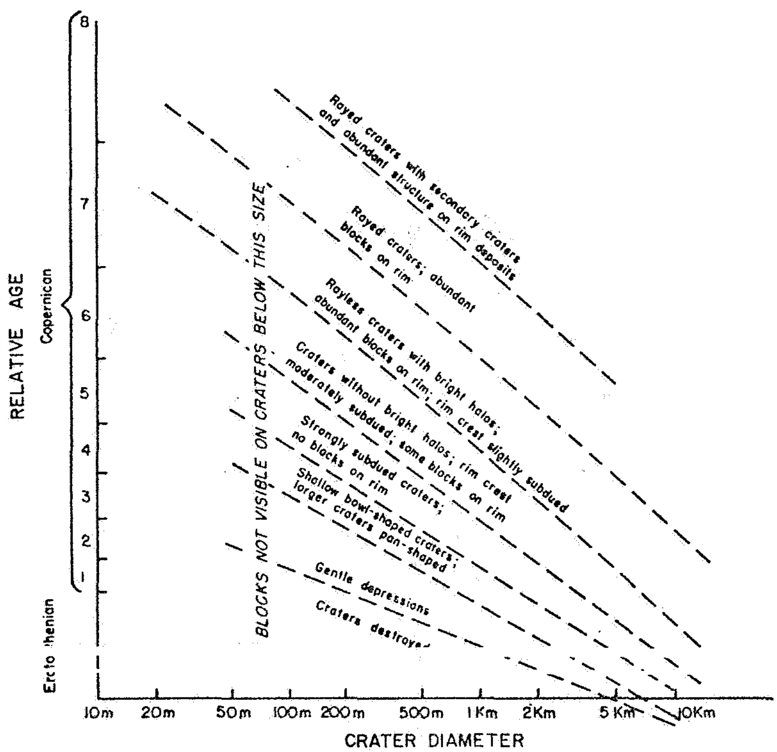

Figure 3.--Relation between diameters, properties, and ages of craters. Categories are intergradational.

relative ages assigned to the oldest craters. Craters that came into being at the same time but with differing depth-diameter ratios would, after considerable degradation, appear to be of different ages according to figure 3. Also the rate of degradation may be higher on lunar slopes than on level ground, so that craters of the same size and morphology in these two environments might not actually be of the same age. The chief utility of classifying craters according to their geologic age lies in planning geochemical sampling in a local area. Samples of ejected blocks from craters with a wide variety of ages will provide material that has been exposed to radiation from space for varying lengths of time. Such a suite of samples will yield information on the effects of radiation with time and possibly on the history of the radiation itself. Evidence bearing on the origin of craters, such as shock phases, is most likely to be found in the youngest craters but may be missing in degraded craters.

The distributions of craters of various ages may also give information on the ages of the surfaces on which they occur. Craters designated 1 and 2 are considerably larger on sites in Mare Tranquillitatis, Sinus Medii and eastern Oceanus Procellarum than on sites in western Oceanus Procellarum. Much of the mare material in western Oceanus Procellarum is therefore younger than the mare material to the east. This conclusion is consistent with crater statistics developed over very large areas by Gault and others (personal communication) and with the fact that solid rock appears to be nearer the surface in western Oceanus Procellarum than elsewhere as indicated by the abundance of resolvable blocks around craters as small as 30 m in diameter. Small relatively fresh-appearing domes are also conspicuous in the mare material of western Oceanus Procellarum but apparently are missing to the east. The younger mare material in western Oceanus Procellarum may be different chemically and mineralogically from the older mare material to the east. Early Apollo missions should be planned so that both of these two contrasting areas of mare material can be visited.

Progress has also been made in mapping mare subunits in Apollo sites. Stereoscopic examination of large-scale Orbiter photographs has revealed the presence of many ill-defined, discontinuous sinuous scarps which may be the remnants of flow fronts like those photographed in Mare Imbrium at Orbiter site V-38. Chemical and physical differences among the mare materials may be present across these scarps. Many low hitherto unrecognized ridges have also been mapped. These low ridges appear to be the older, more cratered and worn-down equivalents of the higher, better-defined mare ridges. They suggest that mare ridge development, like crater development, may have continued over an extended period of time. Around some mare ridges, there is a suggestion that the ridges may have been the site of extrusion of some of the mare material. In the young mare material of Oceanus Procellarum, approximately 40 low circular domes, 100-300 m in diameter, have been recognized. These features also appear to be related in some way to the extrusion of the mare material.

Orbiter photographs both of Apollo and non-Apollo sites were examined for features which might be useful in determining the engineering properties of the lunar surface materials or to extrapolate properties beyond the Surveyor sites. Features sought included: (1) Block tracks and their associated blocks, (2) craters and associated secondary craters, (3) fresh craters with or without blocky ejecta, (4) small craters showing evidence of slope failure, and (5) variations in crater shapes. Some 290 block tracks were found (Grolier, Moore, and Martin, in Ref. 6). These were sought because the tracks and their associated blocks might be used for both static (Refs. 7; 4, p. 107) and dynamic analyses of soil properties. Preliminary static analyses of three blocks at the end of tracks shown in photographs of Apollo site A-1 (V-8) yielded mass bearing capacities between 10^3 and 10^4 g per cm^2 on footings of one to several meters radius and at depths near 0.5 to 1.0 m. Block densities were taken as 2.7 g per cm^3. Nearly 30 lunar craters were found with secondary impact craters and blocks that could be associated with their corresponding secondary impact craters (Moore and Lawry, in Ref. 6). These secondary craters and their blocks will be studied further to try to assess engineering properties along lines previously suggested (Moore, in Ref. 5, p. 108-120; Moore, in Ref. 4, p. 106).

Studies of ejecta showed that the peripheral margins of some lunar craters were extremely rough and blocky and comparable to those around experimental craters produced by explosives at the Nevada Test Site (Robertson, in Ref. 5, p. 122-124). Slope failures were found on many small craters with slopes ranging from 20° to 45°. The slope failures are currently being studied. Variations in crater outlines and profiles may result partly from layers with differing properties (Refs. 8; 9; Moore, in Ref. 4, p. 108; Eggleton, in Ref. 4, p. 111), but estimates of the thickness of the lunar soil layer made from such variations in crater morphology were ambiguous (Stuart-Alexander and Moore, in Ref. 6; Harbour, Ref. 10).

IV. Ranger geologic mapping

Work on geologic mapping from Ranger photographs was slowed during the past year by the precedence given to Lunar Orbiter screening operations and the initial phases of Apollo site mapping. Although not all maps of the Ranger series have been completed, the preliminary work done on all of them provided a sound base from which to begin both of these later activities.

A preliminary 1:50,000-scale geologic map of part of the floor of Alphonsus (RLC 15) was completed by J. F. McCauley (Ref. 11). The map shows the distribution patterns of four floor-filling units of differing ages and craters with three distinct types of exterior rim morphologies. The degree of degradation of all craters greater than 300 m in diameter was estimated by considering the percentage of the floor appearing in shadow on the photographs used. Impact and volcanic craters are both present.

A preliminary map of a portion of Mare Cognitum at a scale of 1:100,000 by S. R. Titley demonstrates the intensity of modification of the mare surface by a Tycho ray. The modification consists of grooves, elongated craters, crater clusters, and chains of craters connected by grooves. The elongate features are oriented north to north-northwest approximately radial to Tycho. Similar intense modification of the mare material by Tycho rays in other areas is clearly visible in Lunar Orbiter photographs.

A closeup view of the Ranger VIII impact area is provided by a preliminary 1:5,000 scale map (RLC 11) by P. J. Cannon. This is one of the first maps made at this large scale and may well serve as a prototype for large-scale maps of potential Apollo landing sites to be used on board the spacecraft and in the mission control center. Craters are classed into five categories on the basis of morphology, and several morphologic units within the mare material are recognized.

A map of a portion of Mare Tranquillitatis (RLC 9) at a scale of 1:50,000 was completed in final form and submitted by N. J. Trask for technical review. Progress on all the Ranger maps is shown in table 5.

Table 5.--Maps of Ranger sites in preparation. Percent completion and estimated completion of final refers to author's work; review, drafting, and printing require 8 to 10 additional months

Map	Scale	Author	Percent completion: Preliminary Oct.	Percent completion: Preliminary 1 Dec.	Percent completion: Final (Dec.)	Estimated completion
RLC 2	1:500,000	Eggleton	80	80		4/68
RLC 3	1:100,000	Titley	50	90		2/68
RLC 4	1:10,000	Titley	50	50		4/68
RLC 7	1:250,000	Wilshire (prelim. only)	100	100		?
RLC 9	1:50,000	Trask	100	100	100	12/67
RLC 11	1:5,000	Cannon	50	100		1/68
RLC 14	1:250,000	Carr	100	100	100	12/67
RLC 15	1:50,000	McCauley	100	100	100	12/67
RLC 16	1:10,000	Grolier	50	50		4/68

A topical study by Trask (Ref. 12) on the distribution of craters according to morphology and size based on Ranger VIII and IX photographs was published.

Part B. CRATER INVESTIGATIONS

Field investigations are being concluded at two impact structures, Flynn Creek, Tennessee, and Sierra Madera, Texas. Fieldwork has begun at a third, Gosses Bluff, Northern Territory, Australia, which is larger and is in a clastic rather than a carbonate sequence. Investigation of impact metamorphism is continuing, with emphasis on material from the Ries crater, Germany, and the Bosumtwi crater, Ghana.

Primary objectives in the studies of volcanic rocks include quantitative measurement of volcano and lava flow morphology for comparison with lunar analogs; identification, by morphologic characteristics, of volcanic rocks that contain rock fragments of deep-seated origin; and determination of the effect of principal controls such as depth of eruption, magma composition, and tectonic structures on differences in surface forms of volcanic rocks.

Mapping of craters produced by missile impacts has continued and in addition several craters were trenched and studied, several geophysical studies were conducted, and remote-sensing imagery was obtained for eight craters.

Experimental impact investigations applied experimental data on cratering to selected lunar problems, supported by Ames Research Center, and conducted studies of low-velocity impact penetration in sand.

Flynn Creek Crater

Core drilling comprised the final phase of D. J. Roddy's fieldwork at the Flynn Creek crater, Tennessee. Surface geologic mapping combined with the drilling indicates that the Flynn Creek crater contains a very shallow, bowl-shaped lens of breccia underlain by faulted and folded limestone. Six NX (5.4 cm diameter) cores were drilled along an east-west line within the crater to depths from 84 to 180 m. Two holes were drilled on each side of the central uplift, two holes halfway between the central uplift and the crater walls, and two holes immediately inside the crater walls. The drill cores contain a sequence of bedded dolomite 1 to 2 m thick which is underlain by a graded, bedded dolomitic breccia as much as 15 m thick. No lake beds or fallback deposits were identified in any of the cores. The bedded dolomitic breccia is underlain by a coarse, chaotic breccia with fragments derived from the local strata; the size of these fragments increases near the base of the chaotic breccia. The Hermitage Formation, a 20-m-thick shale with interbedded limestone, is the lowest unit completely brecciated. Extremely incompetent and plastic, it forms the matrix for much of the chaotic breccia. The thickness of the chaotic breccia lens averages about 35 m. No mineralization or volcanic or meteoritic materials were observed in the six cores.

Limestones directly below the base of the breccia lens are highly faulted and folded, but the deformation decreases downward and the rocks are nearly flat lying and relatively undisturbed below about 100 m beneath the breccia lens. The stratigraphic section is repeated between faults in several of the cores, and both normal and reverse faults occur. Folding immediately below the base of the breccia lens extends 30 to 40 m deeper on the eastern side of the crater than on the western wide. A circular high or anticline may be present about halfway between the center of the crater and the crater walls.

The absence of lake deposits and a fallback zone and the occurrence of the bedded dolomitic breccia containing marine conodonts suggest that the shallow waters of the initial Chattanooga Sea occupied the area when the crater formed, probably in early late Devonian time. The core drill evidence of a shallow lower boundary of the chaotic breccia lens and the decrease in deformation in the rocks below the breccia lens indicate an origin involving surface deformation (i.e., an impact). The asymmetry in surface and subsurface deformation suggests that the impacting body traveled from the southeast to the northwest. The very shallow breccia lens, the absence of mineralization and volcanic or meteoritic materials, the types of rim deformation, and the central uplift are consistent with the impact of a low-density body, possibly a comet. The structural information from surface mapping, combined with the core-drill data, strongly suggests that the Flynn Creek crater was produced by the impact of a cometary body.

Sierra Madera Structure

Mapping of the Sierra Madera structure in west Texas was completed by T. W. Offield, David Cummings, K. A. Howard and H. G. Wilshire. The structure consists of a central core of uplifted Permian and Cretaceous carbonate rocks about 3 miles in diameter, a surrounding synclinal depression 1/2 to 2 miles wide, and an outer rim of mainly Cretaceous rocks that are locally folded and extensively cut by concentric normal faults.

Cretaceous rocks in the ring syncline are depressed slightly below regional position, but there is more than 600 feet of structural relief between the ring syncline and Cretaceous rocks of the outer, structurally high zone. The zone beyond the ring syncline is characterized by normal faults downthrown toward the center; pods and dikes of Cretaceous sandstone and shatter-coned Permian dolomite were injected up along some of the faults and other concentric fractures.

Permian rocks of the central uplift are extensively shattered and brecciated, generally without associated faulting or mixing of adjacent beds. The larger rock fragments in these monomict breccias are themselves shattered, and the fractures are filled with recrystallized mylonite. A mixed breccia, composed of rock fragments derived from several formations, occurs in isolated patches that apparently lie unconformably on the underlying rocks, and locally in dike-like bodies that either crosscut or conform to the adjacent structure. The mixed breccia includes individual fragments of monomict breccia and broken shatter cones.

Shatter cones occur in all Permian units in the central uplift and predate folding. When shatter-coned beds are restored to horizontal, the cones point generally inward and upward toward a central focus.

Quartz and carbonate minerals from both brecciated and unbrecciated rocks in the core of the structure have multiple sets of planar features, and the refractive index of quartz is apparently significantly lower than normal. Such deformational features are omnipresent in the mixed breccia.

The oldest exposed beds in the core were uplifted approximately 4,000 feet above their normal position. The center is characterized by steep to inverted beds, and steep folds whose plunges diminish outward. The folds are cut by numerous, generally steep faults. Details of the style of structural deformation in the central uplift indicate that the rocks moved inward as well as upward to arrive at their present position. The structure is not compatible with any of the most strongly supported terrestrial models that have been advanced as explanations of cryptoexplosion structures, such as reactivated basement structure, igneous or sedimentary intrusion, or explosion, but is compatible with the hypothesis of an impact origin.

Gosses Bluff Structure

Gosses Bluff, in the Amadeus Basin about 120 miles west of Alice Springs, Northern Territory, Australia, is a circular range about 3 miles in diameter rising about 800 feet from the surrounding plain and encircling a hollow about 1 1/2 miles in diameter that is only slightly higher than the outside plain. Intense disturbance of bedrock is exhibited not only in the Bluff but in a circular area with a diameter of about 15 miles centered on the Bluff. On the basis of reconnaissance by the Australian Bureau of Mineral Resources and by commercial exploration groups, the Gosses Bluff structure has been variously considered to have originated by diapiric action, by volcanic or cryptovolcanic activity, or by impact. A joint project of the U.S. Geological Survey and the Australian Bureau of Mineral Resources to carry out a complete geological and geophysical study of the structure began in the 1967 field season.

D. J. Milton and P. R. Brett of the U.S. Geological Survey and G. Berryman of the Australian Bureau of Mineral Resources spent 3 months in the field; P. J. Cook of the Australian Bureau of Mines spent 2 weeks. Principal effort was put into mapping the Bluff proper and the interior hollow on enlargements to approximately 1" = 300' of low-level aerial photographs furnished by Exoil Pty., Ltd. This mapping is now virtually complete.

The high Bluff is composed of Mereenie Sandstone and sandstones and siltstones of the lower Pertnjara Group; the interior is underlain by less-resistant sandstones, shales and siltstones of the upper Larapinta Group. The basic structural units in this area are vertical or steeply dipping bedrock plates, each extending on the average perhaps 500-600 feet along strike and with upper and lower boundaries commonly following horizons of incompetent beds. Some open folding and minor faulting occurs within individual plates, but major changes of attitude generally correspond to clearly defined faults separating plates. Some plates are terminated along strike by faults that cut across at a high angle, but just as commonly the bedding-plane faults above or below gradually curve to cross the bedding at a small angle. Through-going radial faults are conspicuously absent.

The strikes of the plates range from concentric to the structure to radial; the facing is to the outside. Very commonly in plan the plates appear to have slid past one another on surfaces nearly concentric with the structure so as to overlap en echelon or to lie parallel, doubling part of the section. In at least one place where strikes are concentric with the structure, a pair of convergent faults cutting the bedding at a small angle have allowed the plate between them to slide laterally telescope-fashion, wedging the beds apart. In some places where plates abut along approximately radial faults, the strike curves outward into the fault in both plates rather than showing the opposed directions of drag usual along ordinary faults. These observations indicate that the plates have moved inward and upward from their original flat-lying position to lie on a shortened perimeter. The centripetal movement, which seems to rule out either a diapiric origin or a "cryptoexplosion" with a focus at depth, seems most likely to be the consequences of centralized uplift beneath the focus of a shallow explosive-type event. In conjunction with the evidence of high-shock pressures, the only mechanism that can account for such an event is impact.

The polygonality of the structure is in part a consequence of tendency of the more competent units to deform as elongate plates. The marked asymmetries in the structural style around the Bluff, however, remain to be explained.

As the plates were emplaced, their upper edges fragmented to form breccia in what was presumably a crater floor. Such breccia is preserved in numerous patches that occupy perhaps 10 percent of the area of the Bluff proper. Plates of the more competent beds (notably a silicified sandstone at the top of the Mereenie lower unit described below) maintained their coherence furthest and formed bedrock walls against monomict breccia of adjoining weaker beds. In many places these walls toppled over outward (or possibly were projected with their original momentum) to lie as large blocks or somewhat broken plates gently dipping face down, or even vertical and facing inward, on top of breccia of stratigraphically higher beds. Many of the areas of breccia occupy valleys within the Bluff, suggesting that the present topography of the Bluff (presumably, but not necessarily, excepting the central hollow) fairly closely reflects the bedrock profile of the original central uplift.

Gosses Bluff appears to be the outstanding structure in the world at which to study shock-produced fracturing. Only qualitative observations were made this field season; quantitative measurements remain to be made. Complete shatter cones are scarce, but fracture surfaces with the characteristic striations of shatter cones are commonly found in random hand specimens. The nature of the shatter fracturing (as it may be called) is controlled by the rock involved--certain beds are characterized by cone segments 5-6 feet long, others by very short cones or none at all. Shatter fracturing is initiated at discontinuities in the rock; worm tubes normal to the bedding, for example, commonly serve as cone axes. In some units shatter fracturing is expressed not by cones but by several sets of planar fractures. The intersecting sets cut the rock into rhombohedral blocks, and in some units the ends of the rhombohedron grade from three-sided angular corners into rounded shatter cones. The geometry of the planar fracture pattern differs markedly from that of intersecting cleavages or joints in any ordinarily deformed rock. Planar shatter fracturing has not previously been reported from any structure and should be much more useful than simple cones in determining the stress pattern during the shock event.

Reconnaissance indicates that the greater the distance from the center of the structure, the greater the angle between the normal to the bedding and the shatter cone axes; this relation suggests a focus above the original elevation of the beds. More interestingly, cones in plates concentric with the structure are bilaterally symmetrical about a plane normal to the bedding, while in plates oriented at an angle or radial to the structure, the cones are asymmetric, with axes pointing inward after rotation of the bedding back to the horizontal. Measurement of shatter fracturing geometry should aid greatly in determination of the original orientation and perhaps even position of the plates that compose the Bluff.

Only reconnaissance was done in the structure exterior to the Bluff proper. The east peak of Mt. Pyroclast is composed of mixed and highly shocked breccia very similar in appearance to suevite at the Ries crater, Germany. This apparently overlies less shocked monomict breccia. Hydrofluoric acid treatment of promising specimens for detection of coesite and stishovite is in progress.

Some observations of significance to the regional stratigraphy were made. A sharp contact was found in the Mereenie Sandstone between a lower unit 400-500 feet thick, consisting of uniform thin-bedded sandstone with no worm tubes, and an upper unit 800-1,000 feet thick consisting of more varied thick- and thin-bedded sandstones with several zones of vertical worm tubes. At the base of the upper unit is a zone 10-50 feet thick consisting largely of red sandstone. The fossils found by P. J. Cook and identified by J. G. Tomlinson as fragments of arthrodire armour of Devonian age occur not in the Pertnjara red beds but in the red sandstone at the base of the upper Mereenie within one of the overturned displaced blocks of the type mentioned above that lies adjacent to Pertnjara beds. This is the first datable fossil from the Mereenie and confirms the Devonian age that has been suggested on the basis of correlation with other basins. Very limited reconnaissance suggests the possibility, however, that the contact between the lower and upper units corresponds to the base of the Mereenie in the Macdonnell Ranges, and the lower unit may be in fact a unit in the Ordovician Larapinta Group that is absent in the Macdonnell Ranges but occurs at Gosses Bluff and in the James Ranges to the south.

Impact Metamorphism

A paper in press entitled "Pressure and temperature histories of impact metamorphosed rocks--Based on petrographic observations," by E. C. T. Chao interprets the observed shock effects on granitic and other crystalline and metamorphic fragments in the fallout breccia of the Ries crater of southern Germany and the Lake Bosumtwi crater of Ghana, Africa. Features of deformation, evidence of partial or complete and selective phase transitions, and evidence of breakdown, decomposition, or melting of quartz, plagioclase, biotite, amphibole, magnetitie, ilmenite, titanite, rutile, and zircon are described and clarified.

In order to interpret the shock features, diagrams showing the pressure and temperature histories of fragments metamorphosed by impact-induced shock wave are given in terms of a concept of the formation of the fallout breccia during the crater-forming event. Estimates of the pressure and temperature indicated by the observed shock effects are derived from the comparison with available shock wave experimental data on single crystals of quartz and plagioclase.

From detailed observations and the availability of Hugoniot equation-of-state data on quartz, partial transition from quartz to silica glass observed in quartz can be explained in terms of selective disordering. Such a mechanism can be extended to the interpretation of the vitrification of feldspars by shock. Evidence and arguments presented show that the formation of coesite and stishovite from quartz is not accomplished by direct transition. They were probably derived and nucleated from a metastable dense glassy phase.

In contrast with the results of shock wave experiments on single crystals, the effects of natural shock on rock are a great deal more complex. The role of bulk density, porosity, modal mineral composition, the compressibility or shock impedance and the thermal conductivity of one mineral with respect to adjoining minerals, water content, and macrostructures such as mineral banding, bedding, joints, and fractures are briefly discussed. The volume and phase changes throughout the compression and expansion stages of the event are considered. Recrystallization and criteria of the cooling histories of shock-heated fragments are also discussed.

By correlating the shock features with peak pressures and temperatures, the degree of impact metamorphism under nonequilibrium conditions can also be determined. As an example, the impact-metamorphosed granitic rocks of the Ries are classified into seven categories.

The shock phase project of D. J. Milton was largely devoted to preparation of a comprehensive review of the geology of terrestrial impact structures, of which the first draft is now completed.

Volcanic Studies

Mule Ear diatreme.--Investigation of the Mule Ear diatreme, Utah, was reactivated in June 1967. Detailed mapping was continued by Desiree Stuart-Alexander at the scale used by Shoemaker and Moore in 1957 and Moore in 1962; the final map compilation, scheduled for FY 1968, awaits a joint field check by all mappers.

Formation and enlargement of the Mule Ear vent occurred by spalling and ejection, presumably along a fracture or weak zone. Country rocks in contact with the diatreme are not folded or faulted. Multiple explosion periods resulted in a zonal distribution of rock fragments within the vent, so that the core contains mainly rocks from the lower part of the vented area (perhaps the basal 2/3 or 1/2) which were all mixed within a few feet or tens of feet, and the perimeter contains fragments from the entire cross-cut section, with the upper part being most heavily represented.

Preliminary laboratory analysis of rock specimens has begun. Procedures to date include primarily petrographic examination and limited X-ray mineral determinations. These data suggest that carbonatization has occurred on a large scale; the "kimberlite" mineralogy seems to be mainly chlorites and clays with very little serpentine so far detected. A suite of specimens is being chemically analyzed to determine the nature of the additive materials.

Moses Rock diatreme.--A detailed study of the Moses Rock diatreme, Utah, was completed by T. R. McGetchin. Field investigations led to the following conclusions: 1) The breccias were fluidized when emplaced because they are particulate on all scales, they have size-frequency distributions like comminution curves, fragments from widely separated positions are intricately mixed on all scales, and kimberlite components are greatly dispersed; 2) no silicate melt existed at the present level of exposure; 3) the dike grew laterally parallel to tensile fractures by slumping or spalling of wallrocks into the dike; these fragments then became comminuted and mixed with the erupting material, and transported according to their size, shape, and density; 4) sedimentary fragments transported upward in the dike have an inverse size-depth relationship; when applied to fragments of crystalline rock, this provides an empirical rationale for reconstruction of the vertical sequence based on size; 5) fragments are displaced downward a maximum of 1,500 feet, providing a minimum figure for the overburden at the time of eruption; and 6) calculation of the settling velocity of the largest fragments displaced upward in the dike suggests that the upward flow velocity (for assumed fluid density) was at least 10 to 50 m per sec.

Petrologic investigations led to the following conclusions: 1) Compositions of coexisting clinopyroxene-orthopyroxene and orthopyroxene-pyrope indicate equilibrium conditions at 95 ±5 km depth and 950° C ±60° C, the depth and temperature of the kimberlite reservoir; 2) size-depth relations and relative abundance of crystalline fragments suggest that the crust consisted of granite and abundant metabasalt near the surface; gabbro, diorite, amphibolite at intermediate depths; and retrograded basic pyroxene-granulite with minor zoisite-eclogite at greater depths; 3) dense fragments include true eclogite, spinel-bearing websterite, rare spinel-lherzolite, and abundant serpentine-tremolite schist; all except the spinel-lherzolite contain minerals distinctly different in composition from those in the kimberlite and are inferred to be accidental inclusions sampled from the vent walls during the eruption of the kimberlite; 4) source rock for the kimberlite was garnet-lherzolite; 5) the erupting kimberlite is inferred to have been a volatile phase, principally water with CO_2 and particulate grains of mainly olivine; 6) the abundance of the serpentine-tremolite schist suggests a hydrated upper mantle; 7) the upper mantle above 100 km may be phase-layered: the upper part spinel-lherzolite, the lower part garnet-lherzolite.

Lunar Crater volcanic field.--The Quaternary Lunar Crater volcanic field, an area of alkali basalt in the Pancake Range of northern Nye County, Nevada, contains a wide variety of morphologic features including cinder cones, spatter-and-cinder cones, and maars that are being studied by N. J. Trask and D. H. Scott. Lunar Crater itself is a maar, approximately 1,200 m in diameter, which resembles in morphology many craters of comparable size on the Moon. The volcanic field is of special interest because of the presence of ultramafic inclusions in the ejecta and flows surrounding several of the vents. Most of the flows and vents occur in a northeast-trending band about 30 km long and 5 to 8 km wide. This band is situated within an elevated valley surrounded on three sides by outward-dipping beds of Tertiary ignimbrites and related silicic volcanics typical of the Basin and Range Province.

Structural and stratigraphic relations within and between the Quaternary basalts, the surrounding Tertiary ignimbrites, and slices of Paleozoic sedimentary rocks within the ignimbrites are being studied by D. H. Scott. Five mappable units within the Paleozoic rocks and nine separate cooling units within the ash-flow tuffs have been identified and correlated. Although the ash-flow tuffs partly surrounding the basalt field form a roughly circular series of arcuate plateaus, unconformities between ash flows as well as substantial thickness variations within units suggest that the present topography in the adjacent area does not necessarily reflect the presence of an ancient caldera. Basalts rich in olivine and plagioclase phenocrysts are exposed in the walls of Lunar Crater and are among the oldest Quaternary basalts in the field. Some of the younger flows are jagged scoriaceous autobreccias with individual blocks exceeding 10 feet in diameter. The youngest flows bear abundant ultramafic inclusions and xenocrysts derived from these inclusions.

Unconsolidated to poorly consolidated ejecta making up the raised rim of Lunar Crater and of a second maar to the north, known locally as Grandfather's Chair, consists of vitric lithic tuffs containing rounded to subangular fragments of the basalt flows exposed in the walls and of fragments of the Tertiary ignimbrites. Very little doming of the underlying basalts and ignimbrites apparently occurred at the time of eruption. Fragments range from microscopic sizes up to 2 m in diameter with lapilli sizes predominating.

Ultramafic xenoliths are abundant in flows that issued from a cinder-and-spatter cone at the north end of Grandfather's Chair and from a cinder cone and nearby low linear vent 5 km to the north. They also occur in cores of bombs around the cinder cone. Among the inclusions examined to date by N. J. Trask, most are wehrlite and pyroxenite, but one inclusion of lherzolite has been noted. This is of significance because of the widely held opinion that lherzolite inclusions are either pieces of the earth's mantle or refractory residues formed by partial melting of the mantle (Refs. 13-15). Metamorphic textures have been noted in several of the inclusions, and olivine with well-developed cleavage is a common and somewhat surprising constituent. Although relatively large xenoliths are confined to only a few flows, some xenocrysts of olivine, glassy pyroxene, and plagioclase occur in most of the Quaternary basalts.

This investigation is part of a program designed to establish criteria by which volcanic eruptions that have brought up deep-seated material may be identified; such criteria will aid in the identification of analagous features on the Moon that may provide direct information on deep-seated lunar rocks. Regional mapping will be completed in FY 1968, and a final report is scheduled for FY 1969.

San Francisco volcanic field.--Work on the morphology and general geology of the lunar volcanic analogs of the San Francisco field near Flagstaff, Arizona, was begun by J. F. McCauley in April, 1967, and has continued intermittently to the present. Emphasis has been placed on three types of features because of their common occurrence in Lunar Orbiter photographs: 1) individual linear to coalescing pyroclastic cones best developed near S.P. crater; 2) a steep-sided flat-topped dome near Merriam crater which is similar in form and scale to those seen in the Marius

Hills region of the Moon (a potential late Apollo landing site); and 3) a small broad low dome or shield volcano called Howard Mesa which is also very similar to some of the Marius Hills domes.

Vertical and oblique aerial photographs of these features have been obtained, and fieldwork is in progress at the flat-topped dome near Merriam crater. Initial work suggests that it is the product of early magmatic inflation and later collapse as lavas drained from its flank. Preliminary field reconnaissance has been completed at Howard Mesa, but detailed fieldwork will have to be deferred until spring because of snow cover. Completion of a final report is scheduled for early 1969.

Ubehebe Crater.--A preliminary study was made of the Ubehebe maar, Death Valley, California, by D. J. Roddy. The 10 sq km volcanic field contains basalt flows and younger maars and cinder cones surrounded by basaltic ash. The larger maars, including Ubehebe Crater, which is 230 m deep and 730 m in diameter, are centered on a north-trending fault zone. Smooth, layered ejecta 10-25 m thick surrounds the crater and consists of basaltic ash, cinders, and sedimentary fragments. A minimum volume of 5 x 10^{13} cu cm (10^{14} g) of interbedded conglomerates and sandstones was fractured and removed from the crater. On the basis of reported comminution studies, the minimum energy required to eject the rock was calculated as 8 x 10^{21} ergs. The minimum total energy required to form Ubehebe Crater is 10^{22} ergs if the energies in heating and friction during initial stages of deformation are neglected. An energy of 10^{22} ergs is available for work in an adiabatic expansion of volcanic gases and (or) ground-water steam, assuming initial temperatures of 250° C and 10 percent porosity for the sedimentary rock. Gas pressures computed for these conditions are at least 10 times greater than the tensile strengths of these sedimentary rocks and would be sufficient to fracture and eject the mass of rock occupied by Ubehebe Crater.

Topographically, Ubehebe Crater is comparable to certain low-rimmed, steep-walled, bowl-shaped craters seen in the Ranger and Orbiter photographs of the Moon. If a volcanic gas eruption of 10^{22} ergs occurred on the lunar surface under dynamic conditions similar to the Earth, and if only the effect of gravity is considered, the crater formed should be at least 2 times deeper than Ubehebe Crater, about 1.5 times larger in diameter, and 3.5 to 4 times larger in volume.

Other projects.--Two projects described in the work plan for FY 1968 have not yet been started. These are: Maars and cinder cones near Bend, Oregon (L. C. Rowan, project chief), and comparative morphological study of tholeiitic and alkali basaltic craters, Nunivak Island, Alaska (T. R. McGetchin, project chief). Fieldwork on these projects is scheduled to start next summer.

Missile Impact Investigations

During the period July 1, 1966-September 30, 1967, maps of 18 missile impact craters and 3 explosive craters were prepared, 4 missile impact craters were trenched, 4 remote-sensing flights were flown, seismic studies were conducted on 5 craters, and passive seismic studies were started.

The data collected by mapping the craters include crater dimensions, volume, target properties, and geologic features which have application to the space program. Target materials, angles of impact, kinetic energies, and diameters of the craters mapped are listed in table 1; the last two types of data are compared with those of other craters studied previously in figure 1. Three craters (19-21) which were not mapped are shown and listed; data for these were furnished by the Commanding General, White Sands Missile Range. The explosion craters (22-24) were produced using 60 percent Amogel #1 by Dr. G. Latham of Lamont Geological Laboratories as part of the calibration of passive seismic equipment (ALSEP). It is noteworthy that the veolicities of some of the missiles can be specified. For example, the missile that produced crater 15 impacted with a velocity of 4.25 km per sec.

Trenching of the missile impact craters to depths of 8.5 feet below the crater rims showed that the floors of the craters were

Table 1.--Data on missile impact craters. Data on three explosion craters (22-24) included for comparison

	Target material	Angle of impact (deg)	Kinetic energy (10^{14} ergs)	Rim diameters Meters	Feet
1.	Sand, over cohesive silt	45.8	25.1	6.41 - 5.73	21.2 - 18.8
2.	Silt, clayey, cohesive	45.8	25.1	5.74 - 5.73	18.9 - 18.8
3.	Alluvium	47.8	13.5	4.50 - 3.77	14.8 - 12.4
4.	Gypsum sand, cemented	47.0	15.8	5.47 - 5.22	18.0 - 17.2
5.		47.0	15.8	5.47 - 4.93	18.0 - 16.2
6.		47.0	15.8	4.38 - 4.26	14.4 - 14.0
7.	Alluvium, weakly cohesive	46.4	20.4	5.66 - 5.52	18.6 - 18.2
8.		46.4	20.4	5.30 - 4.85	17.4 - 15.9
9.		46.4	20.4	5.22 - 4.87	17.2 - 16.0
10.	Alluvium over gypsum	47.8	13.5	5.52 - 4.50	18.2 - 14.8
11.	Gypsum sand, cemented	48.0	16.0	5.66 - 4.99	18.6 - 16.4
12.		48.0	16.0	5.73	18.8
13.		47.0	16.0	5.74 5.58	18.9 - 18.3
14.		47.0	16.0	6.25 - 5.18	20.6 - 17.0
15.		42.3	81.0	8.40 - 7.56	27.6 - 24.9
16.	Colluvium, soil	48.0	13.8	5.02 - 4.93	16.5 - 16.2
17.	Alluvium, over gypsum	47.0	16.5	3.90 - 3.41	12.8 - 11.2
18.	Gypsum lake beds, sopping wet	25.1	44.6	11.3 -11.2	37.2 - 37.0
19.	Gypsum lake beds, wet	Oblique	18.4	6.09	20
20.	Gypsum, clay	"	4.9	3.65	12
21.	Gypsum sand dune	"	11.3	5.48 - 3.05	18 - 10
22.	Alluvium over gypsum	---	9.5	3.41	11.2
23.		---	9.5	3.89	12.8
24.		---	19.0	4.38	14.4

NOTE.--Figures given in the kinetic energy column for the explosion craters (22-24) represent approximate energy release. Depths of burst of the three explosions were 20, 43, and 43 cm, respectively.

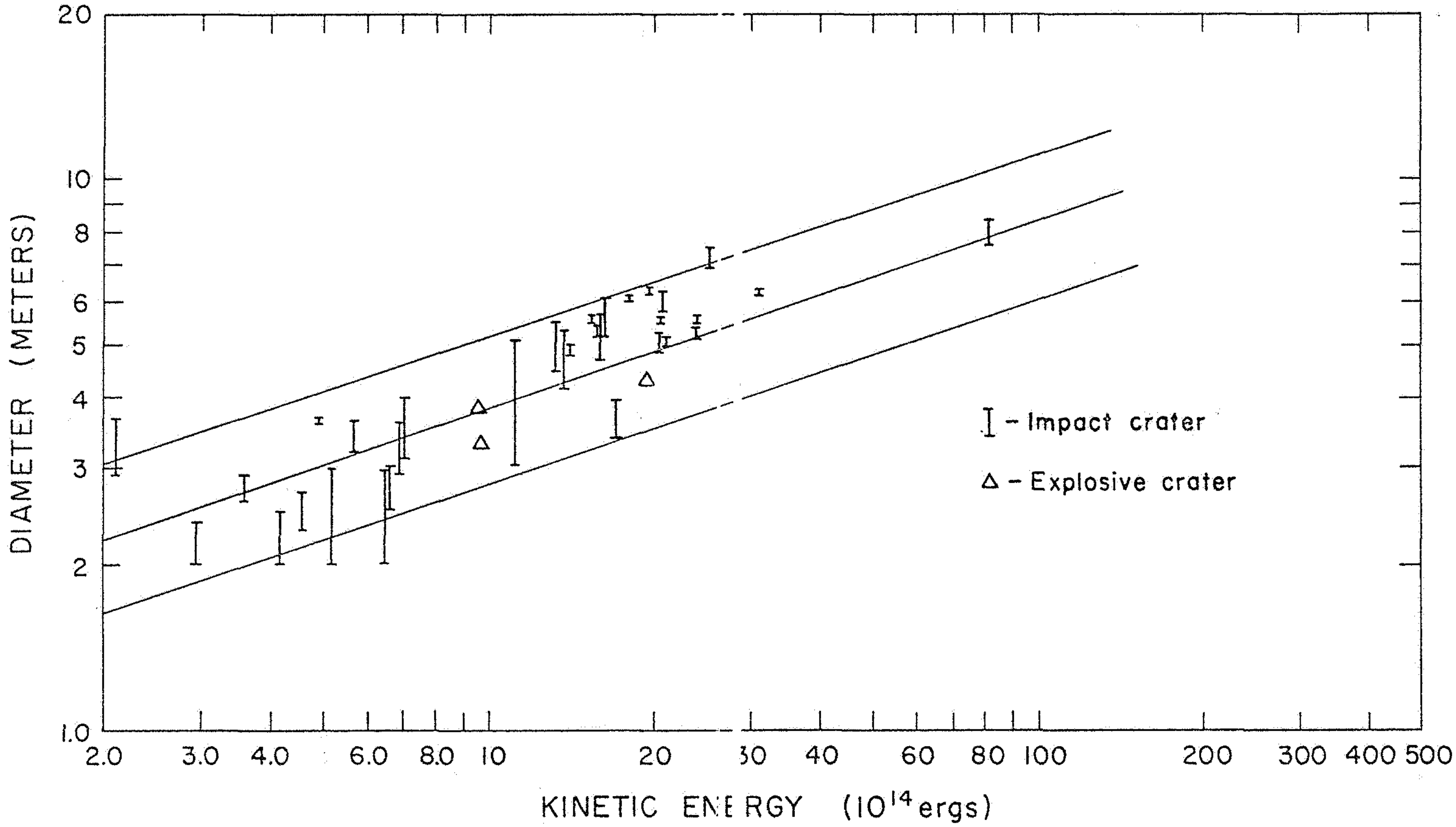

Figure 1.--Comparison between kinetic energy and crater rim diameters for missile impact craters. Approximate energy release for three explosion craters and their diameters are also shown.

underlain by a brecciated mixture of fragments of projectile and sheared and compressed target material. The mixed breccia was overlain by a thin veneer of talus and fallback. A second breccia zone composed of banded brecciated target material was found adjacent to the mixed breccia. This second breccia was banded parallel to the contact with intensely fractured target material, suggesting flowage of the materials. The intensity of fracturing of the target material decreased outward away from the crater, and conjugate fractures were well developed in some craters. Trenching of one crater in a layered target of alluvium and gypsum showed that the deep layers were tilted upward in the down-trajectory direction and at right angles to the trajectory but not in the up-trajectory direction. The layer interface was 1/7 of the crater diameter. In another crater, the layering interface was deeper and little or no upward deflection of the layer was observed. However, in the up-trajectory side, the layer was deformed to a depth of at least 1.0 foot.

Preliminary results using infrared and photographic imagery of the craters obtained from remote-sensing flights indicate: 1) The images on daylight infrared imagery are strongly dependent on topography, but under ideal conditions the image of crater ejecta is excellent; 2) color photography is valuable in delineating ejecta and fallout patterns; 3) images on black and white photography are good but not as clear as color photography; and 4) the ejecta patterns were shown by the ultraviolet photography. (See Ref. 16.) The imagery of the craters was obtained by the Earth Resources Program Aircraft of the Manned Spacecraft Center, Houston, Texas.

Active seismic studies using a hammer energy source and engineering seismometer (MD-3) on 10 foot source-geophone spacings showed a decrease of acoustic velocities from about 3,000 fps beyond one crater diameter to 1,000 fps and less at the crater edge. The decreasing acoustic velocity correlates with increasing fracture intensity and decreasing strengths measured with a shear vane.

Active seismic studies of two craters conducted by Hans Ackermann and Neil Thompson using explosive sources and standard seismic refraction equipment, showed that the time-distance curves for the missile impact craters are similar to those of Meteor Crater, Arizona, and those of the explosion craters at the Cinder Lake Test Site. A computer program is being written by Ackermann to determine the velocity distribution in the crater area.

Passive seismic experiments by G. Latham of the Lamont Geological Observatory were started. Because of damage to lines, possibly caused by the local fauna (field mice), the seismic equipment did not operate properly at the correct time. The calibration shots worked well however.

Experimental Impact Investigations

The experimental impact investigations project applied experimental data on cratering to lunar problems, supported Ames Research Center in a study of repeated impacts in sand targets, conducted limited experiments on low-velocity projectile penetration and constructed components for a low-velocity projector.

As part of Lunar Orbiter Mission Operations Screening, the frequency distribution of blocks around a nuclear explosive crater in flow basalt (Danny Boy) was compared with that around a lunar crater (Site II P-11-B); the two were found to be similar. On the basis of the block counts, the nuclear crater Danny Boy was recommended as a test site for vehicles designed to operate on locally rough lunar terrain (Ref. 17).

Preliminary studies of secondary impact craters around small lunar craters indicate the presence of an easily cratered lunar regolith or soil like layer (Ref. 18). Further investigations are in progress to explore the possibility of using secondary impact craters to estimate the mechanical properties of the lunar surface materials. As a first step, a search of Lunar Orbiter photographs was initiated, and a preliminary list had been made of craters with their corresponding secondary impact craters (Moore & Lawry, Lunar Orbiter V Screening Rept., in prep.). In a Lunar Orbiter II screening report, Moore showed that lunar photographs can be used to extend some terrestrial data to larger features, such as the relationship between largest blocks ejected from a crater and crater diameter (Ref. 19). The application of data on experimental cratering is also discussed in Part A of this report.

As part of a cooperative program of research with Ames Research Center, four topographic maps and four planimetric maps were prepared by R. V. Lugn from stereophotographs of sand targets subjected to experimental bombardment. The experiments were designed to simulate micrometeoroid bombardment of the lunar surface. Three different flux distributions were used, and the effects of slopes on crater destruction were examined. The topographic maps can be used to compare experimental slope-frequency distributions with lunar slope-frequency distributions.

Studies of low-velocity impacts of small rods (1/8, 1/4, and 1/2 inch diam.) with fine-grained sand at velocities up to 630 cm per sec showed that penetration was proportional to the velocity of the rod. Such a relationship suggests that penetration resistance of the fine-grained sand should be proportional to the velocity of the rod. Time-penetration histories recorded by high-speed camera have partly confirmed this, but more data are needed. The time-penetration histories also indicated that accelerations on the rod did not change markedly with depth of penetration, but were nearly constant with penetration.

In order to further study low-velocity impacts, a projector and velocity-measuring system have been built. A vacuum system will be constructed to study penetration and fragmentation resulting from low-velocity impacts.

Part C. COSMIC CHEMISTRY AND PETROLOGY

Three projects in the Astrogeologic Studies group are responsible for most of the work reported here: 1) Chemistry of cosmic and related materials; 2) petrography of tektites; and 3) petrology of meteorites. Separate projects of cosmic dust investigations, though receiving support from different sources, are reported here because they overlap to some extent. Work on tektites has necessarily been related to work on impactites reported on in more detail in Part B, Crater Investigations.

I. Chemistry of cosmic and related materials

1. Chemical investigations and research

   This project continues to provide the chemical research, investigations, and support to studies undertaken by the Branch of Astrogeologic Studies and the Branch of Surface Planetary Exploration.

   a. North American tektites (Cuttitta, Clarke, Carron, and Annell, 1967, see p. 4)

   b. Comparison of Macedon and Darwin glass (Ref. 20)

   c. Multivariate analysis of geochemical data on tektites (Miesch, Chao, and Cuttitta, 1966, see p. 5)

   d. Indochinites - Analytical work has been completed on the determination of the major-element composition and the abundances of 22 trace elements of a suite of 12 tektites from Dalat, Viet Nam, selected to cover the range of indices of refraction and specific gravities exhibited by several hundred indochinite specimens in the U.S. Geological Survey collection. The data are still being evaluated, and a report intended for publication is forthcoming.

   e. Impactites - In collaboration with the impact metamorphism project, four impact glasses (colors: white, grey, green, and black) carefully selected from suevite-like breccia from the Lake Bosumtwi Crater of Ghana were analyzed for major elements and 18 minor elements. The data suggest that: 1) The white glass could have been derived from vein quartz, and 2) the grey glass (predominates in abundance) and black glass are derived from different parent materials (the two glasses differ in total iron, ferric-ferrous ratio, MgO, CaO, Na_2O, K_2O, and H_2O). In order to identify the parent materials of the Lake Bosumtwi impactites, detailed chemical studies have been made of slates, phyllites, mica schists, graywackes, and metavolcanic samples. The 19 specimens studied were selected on the basis of extensive evidence of shock metamorphism. Evaluation of these data is in progress.

f. Phosphorus fractionation (Ref. 21)

g. The distribution of Mn between coexisting biotite and hornblende in plutonic rocks (Ref. 22)

h. Collaborative analytical efforts - Other projects (in situ geologic studies, geologic instruments studies, and advanced systems and geological methods) required concurrent chemical support. Chemical analyses for major and 18 minor elements have been made on 20 basalts from Coconino County, Arizona; 11 drill-core samples from Mt. Diablo, Mono and Inyo Counties, California; and 15 samples of volcanic ash and olivine basalt from Zuni Salt Lake, New Mexico. Abundances of 18 trace elements in 8 samples of whole meteorite and mineral separates were also determined.

2. The strengthening and broadening of Astrogeology's chemical capability and potential

In order to ensure the successful completion of any chemical investigation required by current or contemplated Branch programs, efforts related to methods research and increasing the Branch's instrumental capability have continued, particularly in the areas of atomic absorption spectroscopy, emission spectroscopy, gas chromatography, radiochemistry, and X-ray fluorescence. The conservation of valuable and rare specimens of astrogeologic interest and the capability to obtain pertinent and meaningful chemical data on very small samples are problems inherent in space exploration programs.

a. Atomic absorption spectrometry - This technique is being applied to the determination of refractory elements (Si, Al, V, Ti, etc.).

b. Emission spectroscopy - Studies continue in the application of controlled atmospheres (Ar, He, Ne, and their mixtures) to the spectrographic determination of the more refractory elements such as Hf, Nb, Ta, W, and the rare earths (also see Ref. 23).

c. Gas chromatography - Application of this technique to the determination of H_2O, CO_2, and (or) S in very small quantities of materials of astrogeologic interest (e.g., meteorite mineral separates, chondrules, impactites) is the subject of continuing research.

d. X-ray fluorescence analysis - Research and service work still continue with research efforts being principally focused upon the light major and minor elements where Z = 6 - 12 (C, O, F, Na, and Mg) and also upon the rare earths, and the halogens (Ref. 24).

e. Radioactivation analysis

(1) General multi-element analyses

General multi-element analyses utilizing radiochemical separations and (or) nondestructive instrumental techniques are being developed and used as illustrated by the determination of Ta and Hf in tektites and impactites as a continuing contribution to existing selective volatilization studies. Procedures for determining P, Ta, and Hf in silicates have been developed (Refs. 25, 26).

(2) Achondrite studies

Interrelationships of the various types of achondrites and their evolution are not clearly understood. Studies of the variation of typically lithophilic elements (Ta, Hf, and P), siderophilic elements (Ni, Co), and highly fractionated chalcophilic elements (Cd, In, Tl) can provide a better understanding of their history and their relationship (if any) to ordinary chondrites and the Moon. The determination of Cd, In, and Tl in achondrites was made possible by the recent acquisition of a new low-level beta counter. In order to obtain meaningful data, analytical work concerning these chalcophilic elements will continue to monopolize the new beta counter for probably 1 year.

(3) Instrumental analyses (nondestructive)

The application of coincidence-counting techniques to instrumental analyses of silicates is being investigated. Calculations strongly support the feasibility of determining Co, Cu, Fe, Mn, Na, and Sc by these techniques. Determination of Hf, Cl, and certain rare earths by these techniques also may be feasible. Completely nondestructive, they offer the advantage of permitting subsequent physical and other chemical studies of the same specimen (see Ref. 27 on Co and Cs).

3. Invited contributions to reference textbooks

Three invited contributions were made to textbooks:

a. New instrumental techniques in geochemical analysis (May and Cuttitta, 1967, see p. 5)

b. X-ray fluorescence spectroscopy in the analysis of ores, minerals, and waters (Ref. 28)

c. Gallium (Ref. 29)

II. Petrography of tektites

Three aspects of the problem of the origin of tektites are being studied by E. C. T. Chao.

1. Data have been collected on the chemical variation and characteristics of tektites of every strewn field. They were obtained by complete high-precision chemical analyses of major elements and 21 minor elements in approximately 105 selected tektite samples. Interpretation of these data is pending. The correlation coefficients among 25 parameters are to be interpreted after the closed-system effect has been eliminated through a computer program (Miesch, Chao, and Cuttitta, 1966, see p. 5).
2. Relict mineral fragments have been found in the chunky type of Thailand tektites. Optical study and electron-probe analyses showed that some of these relict minerals are quartz. These minerals are very sparse, small (up to 30 microns), and widely scattered. Methods of identifying such relict minerals are being explored. Identification of these minerals will provide new clues to the specific type of parent material, whether igneous or sedimentary, from which the Thailand tektites were formed.
3. A joint study is being made of shock-produced glasses (Ries and Lake Bosumtwi impactites) and tektites (moldavites and Ivory Coast tektites) (Ref. 30). A detailed petrographic, X-ray, and thermal experimental study of the Ries and Bosumtwi glasses is in progress (Chao, 1967, see p. 3 ; also Ref. 31). Tektite glass resembles the most intensely shocked Ries glass in texture and probably in pressure and temperature history of formation. This is a continuing study to demonstrate derivations of glasses from crystalline materials by shock and to demonstrate the change or lack of change in the bulk composition of the fused glass as compared to the parent material.

III. Petrology of meteorites

1. Robin Brett (1967, see p. 3 ; Brett and Higgins, 1967, see p. 3; also see Ref. 32) continued his investigations of minor phases in iron meteorites as they bear on the conditions of origin of the meteorites. Previous work showing that cohenite is not necessarily a product of high-pressure crystallization was extended by investigations of the cliftonite form of graphite, which was shown to be a decomposition product of cohenite. Others had suggested that cliftonite formed as a decomposition product of diamond, which would require a high-pressure history. Synthesis of cliftonite from cohenite at low pressures effectively demonstrated that the minor mineral phases of iron meteorites do not necessarily indicate a high-pressure history.
2. Brett continued his studies of sulfide crystallization with a review of the origin of lamellar troilite (called Reichenbach lamellae) in iron meteorites (Brett and Kullerud, 1967, see p. 3, also see Ref. 33; Brett and Henderson, 1967, see p. 3). Brett and Henderson showed that lamellar troilite crystallized from a residual sulfide melt after metal phases were crystalline. Several modes of crystallization were identified, and it was proposed that the term "Reichenbach lamellae" be abandoned.
3. M. B. Duke's description of the petrology of eucrites, howardites, and mesosiderites was completed with electron-microprobe analyses of pyroxenes from five meteorites. A lunar origin was proposed for these meteorites on the basis of their petrology and inferences from lunar stratigraphic history (Ref. 34).

IV. Cosmic dust

1. M. H. Carr investigated particulate materials collected from the upper atmosphere by a Luster sounding rocket experiment and a Litton Industries high-altitude (135,400 ft) balloon. Electron diffraction studies of 0.05 - 0.5μ particles collected by the balloon suggest that these particles are an iron spinel, possibly the result of meteorite ablation. Studies of the

Luster samples showed that there were at least 30 times as many particles representative of contamination as there were possible extraterrestrial materials (Carr and Gabe, 1967, see p. 3). Only upper limits to the abundance of extraterrestrial material could be established, but these were at least two orders of magnitude lower than those determined from earlier Venus Flytrap experiments.

2. Results of electron microscopic investigations of samples collected on the Gemini 9 mission were consistent with the Luster results. The number of particles collected was much lower than predicted from earlier measurements.
3. H. T. Millard and M. B. Duke studied magnetic spherules from a deep-sea sediment and spherules collected from the atmosphere (Ref. 35). Magnetite, wustite and α-iron are the principal phases of the deep-sea spherules, which range from 100-400μ in diameter. Only magnetite was found in the atmospheric spherules, which are all less than 30μ. The Ni, Mn, and U contents of the deep-sea spherules support the hypothesis that the spherules are ablation products of iron meteorites. A technique for mounting, sectioning, and polishing small particles for electron-microprobe analysis was described by Finkelman and Duke (Ref. 36).
4. A description of the Shergotty meteorite, a eucrite with uncommon magmatic and shock-metamorphic features, was completed by additional heating experiments on maskelynite. Time-temperature curves indicate that immediately after the maskelynite formed, the temperature of the meteorite remained below 450° C (Ref. 37).

Part D. SPACE FLIGHT INVESTIGATIONS

I. Orbiter

The Lunar Orbiter program has produced a rich photographic data bank upon which studies of regional geology and manned landing sites will be based for years to come. Preliminary studies of Orbiter photographs are summarized in reports on the appropriate mapping programs in Part A, Lunar and Planetary Investigations. Part D is a report of the operations of preliminary planning, site selection, mission flight operations, and post-mission screening in which personnel of the Branches of Astrogeologic Studies and Surface Planetary Exploration participated in support of the Orbiter program (table 1). The purpose of this participation was to assure maximum effective scientific return from the program.

All five Lunar Orbiter missions were successful. All were nearly on schedule, and the entire program was completed within a year (August 1966 to August 1967). The primary objective of the first three missions was to obtain high-resolution (1-2 m) photographs of potential early Apollo landing sites in the equatorial belt, and eight prime sites were selected. Scientific sites of potential interest as later Apollo sites also were photographed however, especially in the later missions. Considerable area on the far side was also photographed by the first three missions.

Missions IV and V were very different from the first three; they obtained photographic coverage of all parts of the Moon by flying a near-polar orbit and were mainly directed at regional and topical scientific questions in addition to local landing site evaluation. Mission IV photographed the entire front side at from 60 to 100 m resolution (except for parts in the east which have either less resolution or--in a 10 degree strip--are badly fogged) and also much of the far side. The invaluable photographs from this mission are now the primary source material for regional lunar studies. (Use of what is probably the single most valuable product of the mission--Mare Orientale photography--is discussed in Part A.)

Table 1.--Geologists and technicians (T) participating in the operational phases of the Lunar Orbiter program. Roman numerals refer to Orbiter mission

Mission planning (only the principal participants are listed; all Branch geologists contributed to site selection)	Mission operations (at JPL SFOF, Pasadena, Calif.)	Screening and Evaluation	
M. J. Grolier	M. H. Carr (IV)	N. G. Bailey (II)	H. A. Pohn (II,III,V)
Harold Masursky	M. J. Grolier (II,III)	P. J. Cannon (V)	F. G. Robertson (III)
L. C. Rowan	H. E. Holt (I)	M. H. Carr (II*,V)	L. C. Rowan (I*,II*,III,V)
D. E. Wilhelms	K. A. Howard (IV)	A. H. Chidester (II)	G. G. Schaber (II,III,V)
S. L. Dowd (T)	T. N. V. Karlstrom (II)	M. D. Crittenden (III,V)	D. L. Schleicher (II,V)
J. R. Running (T)	Harold Masursky (I-V)	David Cummings (V)	D. E. Stuart-Alexander (V)
Anne Umphrey (T)	T. W. Offield (I,III)	D. H. Dahlem (II)	R. L. Sutton (II)
	H. A. Pohn (IV,V)	R. E. Eggleton (I*,II,V)	G. A. Swann (II)
	L. C. Rowan (I)	D. P. Elston (V)	N. J. Trask (II*,III*,V)
	G. G. Schaber (V)	M. J. Grolier (I*,II*,III*,V)	S. R. Titley (II,III,V)
	D. E. Wilhelms (IV,V)	M. T. Hait (II)	G. E. Ulrich (II)
	Anne Umphrey (T) (III)	H. E. Holt (II)	D. E. Wilhelms (II*,III,V)
		K. A. Howard (II,V)	H. G. Wilshire (II,V)
		T. N. V. Karlstrom (I,II,III)	L. C. Calk (T) (I)
		J. F. McCauley (V)	H. J. Gabe (T) (II*)
		J. W. M'Gonigle (II,V)	M. M. Lawry (T) (V)
		G. L. Martin (V)	M. R. Ligon (T) (III)
		Harold Masursky (I*)	R. V. Lugn (T) (I*,III)
		H. J. Moore (II,III,V)	G. M. Nakata (T) (II,III)
		J. T. O'Connor (II)	Gail New (T) (I)
		T. W. Offield (III,V)	J. R. Running (T) (I*,III)
		N. J Page (V)	Anne Umphrey (T) (I*,II*,III*)
			J. J. Wooldridge (T) (I*,II*,III*)

* Participated at Langley Research Center, Hampton, Va.

Mission V, the most nearly flawless of all the missions, produced a quite different product and one that will supplement Mission IV: high-resolution (2½-20 m) photographs of carefully chosen individual scientific sites, as well as new photographs of early Apollo sites, including an important site (V-8) that had not been well covered before. Among the many superb photographs obtained, particularly noteworthy were those of the young craters Aristarchus, Tycho, and Copernicus with their incredible detail of "ponds," "mudflows," blocks, and fractures; of the smaller fresh craters Censorinus, Petavius B, Dawes, Stevinus A, Copernicus H, Dionysius, and Messier; of small fresh volcanic features such as the Hyginus Rille craters, Rima Bode II crater, Gruithuisen-region domes and craters, Tobias Mayer dome, and the Marius Hills; of young dark volcanic deposits such as those near Littrow, Sulpicius Gallus, Copernicus CD, Rima Bode II, and the Aristarchus Plateau; of sinuous rilles such as Hadley, Rima Plato II, Schröter's Valley, and those of the Harbinger Mountains; of distinct flows in Mare Imbrium; and of old terrains such as Eratosthenes, Gassendi, and the Altai Scarp, which will help calibrate young terrains. Mission V also filled in almost all the gaps in photographic coverage of the far side of the Moon. In photographs of many sites, features are visible that provide information on surface engineering properties. Block tracks and the objects that formed them are an example. Many sites will be studied intensively as potential late-Apollo landing sites, and a program of exploration is now being devised that will maximize the geologic product from this rich set of sites.

Each of the first three missions (I, II, and III) was preceded by the selection of primary and secondary photographic sites. Among the geologists who collected data from earlier 1:1,000,000 geologic and terrain maps for the selection and documentation of these sites, J. F. McCauley, L. C. Rowan, D. E. Wilhelms, M. J. Grolier, and Harold Masursky were especially active. Pre-evaluations of the nine Mission I sites, which appeared as Technical Letters Astrogeology 13 through 21, were discussed in Part D of the last annual report. Descriptions of all missions except IV (Lunar Orbiter Proj. Office, 1966-67, see p. 7) were prepared with the help of Survey geologists, mainly L. C. Rowan for Missions I and II, N. J. Trask for Mission III, and D. E. Wilhelms for Mission V. Geologic analyses conducted during the screening and evaluation phase were especially important in planning subsequent missions.

Sites were not selected for Mission IV because it was a whole-Moon survey, but the conduct of this important mission was determined in part by the efforts of Survey geologists, especially Harold Masursky and L. C. Rowan, who succeeded in demonstrating the need for the mission. Nearly all Branch geologists participated in the selection of Mission V sites; their opinions were collected, coordinated, and presented to the Lunar Orbiter Mission V Planning Group by Harold Masursky and D. E. Wilhelms.

During each of the missions, geologists acted as mission advisors at the Space Flight Operations Facility (SFOF) at the Jet Propulsion Laboratory, Pasadena, California, (table 1) providing geologic and photometric information on the individual sites needed by the flight operations crews in monitoring and adjusting the mission.

The screening and evaluation phase consisted of geologic and terrain analyses of the primary photographic sites, leading to recommendations to the Lunar Orbiter Project Office concerning the relative roughness and scientific merits of the sites. On the basis of these recommendations and those of Manned Spacecraft Center scientists and engineers who studied the landability and radar approach paths, subsequent missions were planned and eight potential Apollo landing sites were selected for further study (see Part A). Preliminary analyses and accompanying maps for these sites as well as rejected ones are in four screening reports (Refs. 3 - 6), on which the Manned Spacecraft Center collaborated (Mission IV was not screened). Summaries of Missions I and II were also prepared

(Lunar Orbiter Proj. Office, 1966, see p. 7). Some observations by Rowan on Missions I and II were published (1967, see p. 5). Generalizations that can be drawn about the lunar surface at large scales on the basis of the first three missions were summarized in a paper by Trask and Rowan (Ref. 38), which was in press at the end of the fiscal year.

All three phases involved oral presentations and press conferences in addition to the technical documents. Participants were: L. C. Rowan, I, II, III; T. W. Offield, II; T. N. V. Karlstrom, II; N. J. Trask, III; M. J. Grolier, I, II; J. F. McCauley, I; H. J. Moore, I; Harold Masursky, I-V.

II. Surveyor television investigations

This section of the Annual Report describes work done by the U.S. Geological Survey on behalf of the Jet Propulsion Laboratory under contract WO 3027. The Survey is analyzing high-resolution Surveyor television pictures in order to interpret the geologic nature of the lunar surface and the formative processes acting upon it, as well as to produce geologic and physiographic maps of Surveyor landing sites. E. M. Shoemaker, principal investigator of the Surveyor television camera experiment, heads a U.S. Geological Survey team of 10 to 12 full-time employees. During Surveyor mission operations at the Jet Propulsion Laboratory in Pasadena, California, members of the team mosaic the many small pictures, about 2 x 2 inches, into larger sectors of about 75 pictures. Other members study the newly acquired pictures in order to guide the continuing collection of new data. Surveyor data are later analyzed to determine the nature of the lunar terrain; size distribution of craters and fragments; and the fabric, coherence, and approximate thickness of the surficial layer of fragmental debris, as well as the photometric properties, including colorimetry, photometry, and polarimetry.

Two successful Surveyor missions were flown during the report period: Surveyor III to Oceanus Procellarum and Surveyor V to Mare Tranquillitatis. During the Surveyor III mission about

90 mosaics composed of 4,500 pictures were compiled; the Surveyor V mission produced 180 mosaics totaling over 9,000 individual pictures. During post-mission periods an equal number of semi-improved mosaics are compiled, and each individual picture is annotated with its GMT (time when picture was transmitted to Earth).

Surveyor III landed April 20, 1967, in a subdued, rounded crater about 210 m in diameter and 15 m deep, about 370 km south of the crater Copernicus at lat 2.92° S., long 23.25° W. The crater and spacecraft were located by comparing features in the television pictures with those in a high-resolution Lunar Orbiter III photograph.

The lunar surface surrounding the crater was outside the camera's field of view, but the crater's sloping walls permitted nearby features to be viewed more clearly than would have been possible on flat terrain. The size/frequency distribution of observable craters is closely similar to the mean distribution recorded in photographs of the lunar mare by Rangers VII-IX and Surveyor I. Bright fragmental debris appears to be irregularly scattered over much of the visible finer grained lunar surface. The debris, which covers about 12 percent of the surface, and a finer grained matrix in which it is embedded, together compose a particulate layer of low cohesion. The layer is at least 1 m thick along the upper parts of the crater in which Surveyor III landed, but blocky ejecta around superposed craters indicates the presence of coarser fragments or more coherent material at a depth of not more than a few meters. Small superposed craters near the bottom of the main crater lack blocky rims, indicating that the thickness of the relatively fine-grained debris layer there is probably 10 meters or more.

Although Surveyor I landed on relatively flat smooth mare and Surveyor III landed in a subdued crater about 210 m in diameter, comparisons of the pictures from these different sites indicate that the smaller craters and the fragmental debris are similar in distribution, size, and shape. Most craters at both sites are considered to be of impact origin. Craters with sharp raised rims are associated with angular blocks that are perched on top of the local surface and they are interpreted as being young relative to other nearby craters that have rounded rims and less prominent debris. Similarly, degree of roundness of the blocks is interpreted as reflecting length of exposure to abrading forces; blocks associated with subdued (older) craters are significantly rounder than those associated with raised-rim craters. In addition, the relation of blocks to the surrounding surface suggests that freshly transported blocks are perched on top of the surface and older rocks are buried in varying degree.

Disturbance of surface material by the footpads on Surveyor I and III was similar at the two sites. A soil mechanics surface sampler on Surveyor III made bearing and impact tests and dug four trenches. The geologic conclusion from the footpad imprints and areas disturbed by the surface sampler is that the fine-grained particulate lunar surface material is slightly compressible and has relatively low cohesion.

The normal reflectance of the lunar surface (albedo) was determined at both Surveyor I and III landing sites for different materials observed. The albedo of the fine-grained undisturbed surficial material was 7.3 percent at Surveyor I site and 8.5 percent at Surveyor III site. The blocks or rock fragments at both sites were noticeably lighter; their albedo was about 14 to 19 percent. All disturbances of the surficial materials exposed darker material at depths as small as a few millimeters below the optically observed surface. The albedo of this darker fine-grained material is as much as 20-30 percent lower than that of the undisturbed surficial material. The smooth walls and bottom of the footpad imprints differ photometrically from the undisturbed surface. At larger phase angles they reflect about 30 percent more light than the undisturbed lunar surface material, suggesting that small irregularities, which normally cast shadows, have been partly flattened out by the pressure of the smooth footpads.

Color filters were incorporated in the Surveyor television cameras to enable color differences of lunar surficial materials to be delineated. All the material observed appeared gray.

A topographic map of the visible part of the Surveyor III crater was constructed by utilizing the Lunar Orbiter high-resolution pictures for planimetric control and spot elevations; contour lines were then drawn from interpolation of the spot elevation data. Another contour map of the crater was prepared from photoclinometric profiles derived from Lunar Orbiter III high-resolution photograph H154. It showed a crater ranging from 210 to 230 meters in diameter with a depth of 15 meters. Near the vicinity of the Surveyor spacecraft, the general slope of the crater wall was determined photoclinometrically to be about 12°.

Surveyor V landed September 11, 1967, in the southwestern part of Mare Tranquillitatis, at about lat 1.5° N., long 23.2° E. It first touched down on the edge of a small crater and then skidded downward until footpads 2 and 3 reached the floor of the crater. The television camera's view of the terrain outside the crater was greatly restricted. A topographic map of the landing site is being compiled.

The crater in which Surveyor V landed is elongate in a northwest-southeast direction and is the largest member of a chain of small craters trending northwest. It appears to be a rimless compound crater, about 9 m wide by 12 m long, consisting of two partly merged components separated by a subdued north-trending ridge. The crater is probably a member of the family of elongate craters and crater pairs visible in the Lunar Orbiter V high-resolution pictures of the vicinity of the landing site. It has not been identified on these pictures.

The crater may have formed by drainage of surficial fragmental material into a subsurface cavity or fissure. The lunar surface debris layer is exposed in the walls of this crater. At depths below about 10 cm the debris appears to be composed mainly of clods of shock-compressed aggregates ranging from a few millimeters up to 3 cm in diameter, set in a matrix of less coherent finer particles. Rocky chips and fragments are dispersed as a subordinate constituent of the debris. A few larger fragments, up to 20 cm across, appear to be complex aggregates or individual angular pieces of rocky material.

III. Mars spacecraft

A proposal for an investigation of the stratigraphy and structure of Mars was submitted by Harold Masursky, J. F. McCauley, and D. E. Wilhelms to NASA on October 31, 1967, shortly after cancellation of the Voyager 1973 Announcement of Opportunity. The document outlines a series of graduated exploration objectives and discusses the type of data reduction considered desirable. It is applicable to pre-Voyager orbital missions as well as to later Voyager missions that will utilize landing vehicles.

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